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Sampling to make maps for site-specific weed management

Lori J. Wiles
U.S. Department of Agriculture, Agricultural Research Service, Water Management Research Unit, Fort Collins, CO 80526; lori.wiles@ars.usda.gov

Growers need affordable methods to sample weed populations to reduce herbicide use with site-specific weed management. Sampling programs and methods of developing sampling programs for integrated pest management are not sufficient for site-specific weed management because more and different information is needed to make treatment maps than simply estimate average pest density. Sampling plans for site-specific weed management must provide information to map the weeds in the field but should be developed for the objective of prescribing spatially variable management. Weed scientists will be most successful at designing plans for site-specific weed management if they focus on this objective throughout the process of designing a sampling plan. They must also learn more about the spatial distribution and dynamics of weed populations and use that knowledge to identify cost-effective plans, recommend methods to make maps as well as collect data, and find ways to evaluate maps that reflect management to be prescribed from the map. Foremost, sampling must be thought of as an ongoing process over time that uses many types of information rather than a single event of collecting one type of information. Specifically, scientists will need to identify common characteristics rather than just differences of the spatial distribution of weeds among fields and species, recognize that map accuracy may be a poor indicator of the value of a sampling plan, and develop methods to use growers' knowledge of the distribution of weeds and past spatially variable management within a field for both making a map and recommending a sampling plan. The value of proposed methods for sampling and mapping must also be demonstrated or adoption of site-specific weed management might be limited to growers who enjoy using sophisticated technology.

Key words: Geostatistics, scouting, spatial correlation, spatial dependence.

Growers may be able to control weeds with less herbicide with site-specific weed management (Johnson et al. 1997); however, they will not adopt this strategy until there are cost-effective sampling plans to map weed populations in their fields. Sampling to determine whether pest control is economically justified is a fundamental principle of integrated pest management (IPM) (Pedigo 1993), and sampling has become an effective decision-making tool for insect management. However, weed scientists did not become interested in sampling until growers needed cost-effective plans to estimate average weed density or pressure in a field to use postemergence weed management models. Most methods used to develop sampling plans for use with weed management decision models were based on the paradigm of sampling for insect management established by entomologists (Berti et al. 1992; Gold et al. 1996; Johnson et al. 1996a; Krueger et al. 2000).

A sampling plan for IPM describes how to collect information about a pest population in a field to make a control decision (Ives and Moon 1987). A plan specifies the size and shape of sample units, the number and the method for choosing the locations of sample units, and the information obtained from each unit. Most IPM sampling plans are designed for most cost-effective estimation of average pest density in a field to determine whether the pest population is above the economic threshold for control.

The paradigm for designing sampling for IPM is not sufficient for designing sampling plans for site-specific weed management. IPM sampling plans are optimized for characteristic variability of observations of pest density. Variability is described with a dispersion index or frequency distribution of counts (Davis 1993). However, mapping a pest population in a field requires information on spatial variability of observations within a field. The location of observations is important and must be specified and recorded (Weisz et al. 1995). Consequently, making maps requires more intensive sampling and new methods to design cost-effective sampling plans for site-specific weed management.

If weed scientists are to develop affordable methods for sampling and mapping that lead to cost-effective site-specific weed management, they must think less like statisticians and more like economists. They must study sampling procedures of many disciplines such as plans geostatisticians develop to design strategies for extracting gold from a mine and sampling plans soil scientists propose for prescribing spatially variable application of fertilizers. In addition, weed scientists must focus on the objective of prescribing site-specific weed management, know more about the spatial distribution and dynamics of weed populations and use that knowledge to identify cost-effective plans, recommend methods to make maps as well as collect data, and find ways to evaluate maps that reflect the resolution of management and choice of herbicides and rates. Foremost, sampling must be thought of as an ongoing process that uses many types of information rather than a single event in which one type of information is collected. The necessary shift from the IPM paradigm for sampling is already underway with research on the appropriate resolution of sampling for mapping (Cousens et al. 2002; Heisel et al. 1996; Rew 1997) and comparison of methods to interpolate maps from sample data (Dille et al. 2002a; Zanin et al. 1998).

Focusing on the Decision

The first step in designing a sampling plan is to clearly understand the objective of sampling (Buntin 1994). The objective of sampling to use most weed management decision models is clear: estimating the average weed population of a field to select the best uniform herbicide application. In contrast, the goal of site-specific weed management may be general weed management, optimal management of a particular species or detection of sparse patches of an invading weed species. Spatially variable management may be leaving areas of a field untreated or applying one or more herbicides or different rates of a herbicide. The appropriate resolution of sampling and accuracy of a map will depend on the critical densities to be detected and the resolution of patch spraying or, for growers without patch sprayers, the choice of management units for a field. Weed scientists must develop sampling plans based on both why and how site-specific weed management will be done.

Spatial Distribution and Dynamics

Successful sampling to prescribe site-specific weed management is obtaining sufficiently accurate information about spatial continuity of weed populations at minimal cost. The information must only be accurate enough to effectively prescribe site-specific management. Spatial continuity describes the pattern of variation of values with distance and direction (Rossi et al. 1992). In the context of mapping, if you were walking down a crop row, spatial continuity describes how valuable information about the weed population at your starting point is for predicting the weed population at various distances down the row because a map is made by estimating values for unsampled locations from values at nearby sampling locations. Estimates are based on assumptions about the nature of spatial continuity (Isaaks and Srivastava 1989). The challenge of developing sampling plans for mapping is that the information about spatial continuity depends on both the nature of spatial continuity and how sampling was done (Isaaks and Srivastava 1989). Consequently, information about spatial continuity of a species within a field obtained with a sampling plan may indicate other ways to sample to more accurately describe spatial continuity or, if the information about spatial continuity is believed to be sufficiently accurate, to obtain the same information at lower cost.

A variogram may be used to describe spatial continuity for both designing cost-effective sampling plans and making maps (Burgess et al. 1981; Burrough 1991). Each point on a variogram is the average similarity between pairs of observations at locations separated by that distance. Similarity is described as the average squared difference of observations (Rossi et al. 1992). Differences normally increase with distance from some value greater than zero and eventually plateau, indicating that variation between observations is no longer related to distance (Figure 1). Values of a variogram are fit with a model or equation to make a map. Parameters

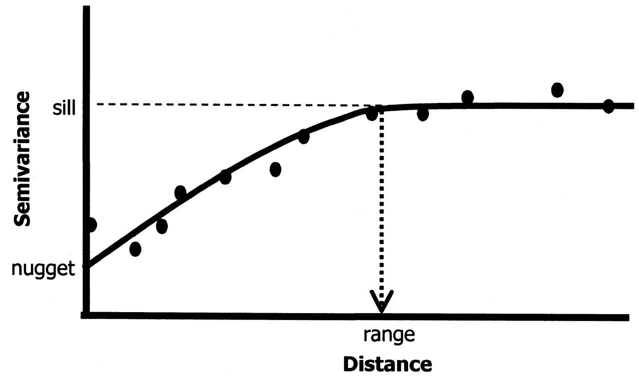

Figure 1. Variograms describe the relationship between distance and semivariance, a measure of similarity of observations, and have been used to model the spatial continuity of weed populations.

of the model are the nugget, sill, and the range (Isaaks and Srivastava 1989). These are the y intercept of the model, the value of the plateau, and the distance at which the variogram reaches the plateau.

A variogram model highlights important features of spatial continuity that influence the cost-effectiveness of sampling. Values of the nugget, sill, and range can guide choice of sample unit and sampling grid for cost-effective sampling (Burrough 1991; Flatman et al. 1988; Oliver et al. 1997; Weisz et al. 1995). For example, the magnitude of the nugget compared with the sill indicates the potential quality of a map made from the sample data or if making a map should be attempted at all (Weisz et al. 1995). Ideally, when making a map, we would like all the observed variability between values (estimated as the sill) to be because of only and all spatial pattern, but some of this variability is due to sampling error or spatial pattern at a finer resolution than the scale of sampling (estimated as the nugget). Therefore, if the nugget is large relative to the sill, then accuracy of any map made from the sample data will be poor. Furthermore, if the nugget is equal to the sill, then there is no basis for making a map because none of the variability can be modeled as spatial pattern. However, because perceived spatial continuity is influenced by the sampling plan, modifying the sampling plan may reveal more about the actual spatial continuity (Rossi et al. 1992). For example, the nugget may be reduced and the map accuracy improved by sampling on a smaller grid or with a larger sampling unit (Burrough 1991; Weisz et al. 1995). More of the spatial continuity of a weed seed bank may be detected by combining and then subsampling several soil cores collected at the same location (Burrough 1991).

Choice of sampling grid may be more critical than sampling unit size for an accurate weed map (Cousens et al. 2002). Primarily square grids, of various sizes, have been used to sample weed populations. The value of the range may guide choice of a sampling grid for more accurate information about spatial continuity. The range of a variogram is an estimate of the average distance within which observations are correlated (Rossi et al. 1992). Because observations must be correlated to be of value for making a map, sampling locations must be separated by several distances smaller than the range to model spatial continuity (Weisz et al. 1995). Moreover, if the map is to be useful for prescribing spatially variable management, observations also must be separated by several distances shorter than the resolution of management.

If the range varies with direction (anisotropy), spatial continuity may be more accurately described at a lower cost with a rectangular grid than the usual square grid. Observations of a weed population may be correlated over longer distances in the direction of the crop row than other directions if seed is moved within a field primarily by machinery (Colbach et al. 2000a; Wiles and Schweizer 2002; Wyse-Pester et al. 2002). Separate variograms may be estimated for the directions of the crop row and across rows (or the direction of longest continuity and the direction perpendicular to it) to choose the size and shape of a rectangular grid.

The relationship between spatial continuity and cost-effective sampling is significant enough that Burgess et al. (1981) recommends that soil scientists conduct a preliminary survey to identify some features of the spatial continuity of soil properties in a field before devising a sampling plan. Information about common features of spatial continuity of soil properties has led to savings in the cost of sampling and improvement in the quality of the information obtained (Burrough 1991). Few growers could likely afford or have the time for preliminary sampling to make a weed map (Oliver 1999). However, the numerous studies that document the variation in the spatial distribution of weed populations among fields and species (e.g., for weeds in corn [*Zea mays* L.], Clay et al. 1999; Dieleman and Mortensen 1999; Wiles and Schweizer 2002; Wyse-Pester et al. 2002 and soybean [*Glycine max* (L.) Merr.], Cardina et al. 1995, 1996; Clay et al. 1999; Colbach et al. 2000a; Johnson et al. 1996b) in the United States also indicate some of that variation may be explained from past management of the field and demographic characteristics of the weed species. Sampling for site-specific weed management could be more cost-effective if we were able predict some general characteristics of spatial continuity of the population in a field from knowledge of fundamental mechanisms of the spatial dynamics of weed populations and information about the major species present and management history of a field (Hausler and Nordmeyer 1999; Rew and Cousens 2000).

This hypothesis was investigated by modeling associations between field properties, characteristics of weed species, and management practices with the distance of the range and how the range changed with direction for 36 seed banks in eight irrigated corn fields (Wiles and Brodahl 2004). Factors associated with pattern of spatial continuity, and thereby possibly useful for designing a sampling grid, were categories of seed bank density, seed size, dispersal mechanisms for seed, and type of irrigation. Results shown in Figure 2 might be interpreted as a decision tree for choosing the most efficient size and shape of a sampling grid based on information that could be known before sampling. Relative size and shape of grids are illustrated at the bottom of the figure with vertical as the direction of the crop row. Interpretation of the decision tree is from top to bottom. For example, if you know the seed bank density in a field is high (right side of the tree) then a smaller, more rectangular grid would be recommended for species with small seed than large seed. A more practical result is that smaller, more rectangular grids may also be more cost-effective for sampling seed banks in furrow-irrigated fields compared with center pivot–irrigated fields. Spatial continuity of weed populations in irrigated fields is likely to be strongly influenced by tillage. In furrow-irrigated fields, tillage is primarily in the direction of the crop row compared with not consistently in any direction in center pivot–irrigated fields (Wiles and Brodahl 2004).

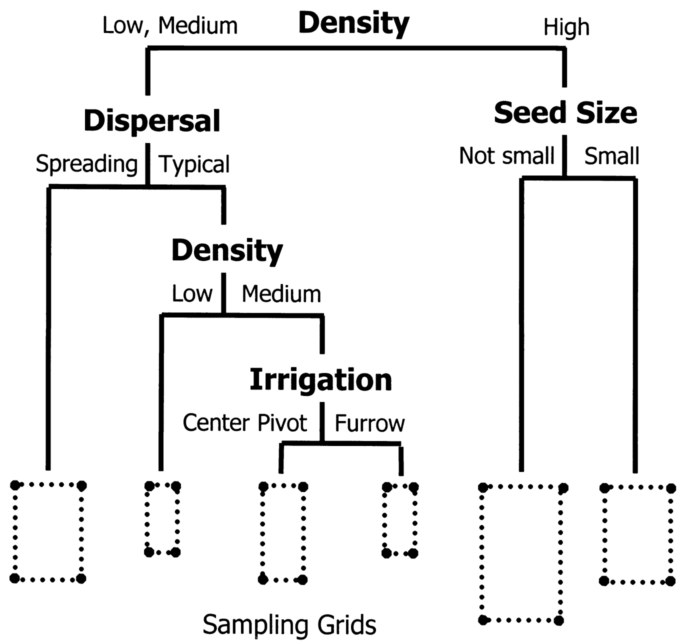

FIGURE 2. A decision tree for relative grid size and shape for sampling weed seed banks in irrigated corn fields in Colorado.

These examples illustrate how knowledge of the spatial dynamics of weed populations could be useful for designing situation-specific sampling plans. These plans should be more cost-effective than a sampling plan designed to be cost-effective, on average, in all situations. Moreover, with knowledge of spatial dynamics of weed populations, we will be able to qualitatively evaluate weed maps by determining whether the spatial continuity depicted in a map is reasonable for the weed species present, field characteristics, and past management practices.

Sampling and Mapping

It is easy to create a weed map from nearly any data set with GIS software, but the map may be a poor representation of the weed population because methods for making maps differ in how spatial continuity is modeled. A map can be inaccurate if the model of spatial continuity of an interpolation method does not represent the observed spatial continuity, particularly with limited observations. Consequently, the value of sampling depends on appropriate choice of interpolation method. Therefore, sampling plans should include recommendations for both collecting data and generating a map from that data.

Most weed maps in the literature were generated with kriging (Cardina et al. 1995; Clay et al. 1999; Heisel et al. 1996; Rew et al. 2001) although simpler methods such as inverse distance weighting can be used (Isaaks and Srivastava 1989). Both methods estimate a value at an unsampled location as a weighted average of nearby observations within a region (a specified search neighborhood) about the unsampled location. Closer observations receive greater weight than farther observations, but the methods differ in how specific a model of spatial continuity for mapping may be for a field. For inverse distance weighting, values are assumed to be inversely proportional to the distance from the point being estimated or to any power of the distance. The choice of power allows assuming different relative weights of nearby and farther observations and thereby different patterns of spatial continuity. This is important because spatial continuity of weed populations may decrease most rapidly over short distances (Cardina et al. 1996; Wiles and Schweizer 2002). With kriging, weights are calculated from a more field-specific model of spatial continuity of a data set such as a variogram or a set of directional variogram models. Moreover, the influence of more than one process on spatial continuity can be modeled, and a search neighborhood may be elliptical for more accurate modeling of variation in the range with direction of oblong weed patches (Isaaks and Srivastava 1989). Accordingly, a kriged map may be more accurate than one created with inverse distance weighting.

Some methods for making maps are better for representing certain patterns of spatial continuity than others (Gotway et al. 1996; Isaaks and Srivastava 1989). For example, kriging is criticized for producing weed maps with less variation in the population at short distances than is realistic (Rew et al. 2001). This may or may not be a problem, depending on the objective and resolution of site-specific management. Stochastic simulation (Rossi et al. 1993) is an approach used for making weed maps that can preserve more of this short-scale variation (Figure 3). Furthermore, a set of equally probable maps may be created with stochastic simulation (Figure 4). Differences among the maps are most obvious for the spatial distribution of high-density seed banks in the lower left corner of the maps and the large area of low density in the top left corner. For example, the area of low density is more contiguous in the top map compared with the others. Equally probable maps generated with stochastic simulation are useful for comparing the risk of creating inaccurate maps with different sampling plans (Faechner et al. 2002). A probability distribution for the value of a sampling plan can be generated from a set of equally probable maps created by stochastic simulation (Rossi et al. 1993). With kriging, only one map and consequently only one estimate of the value of sampling plan can be generated.

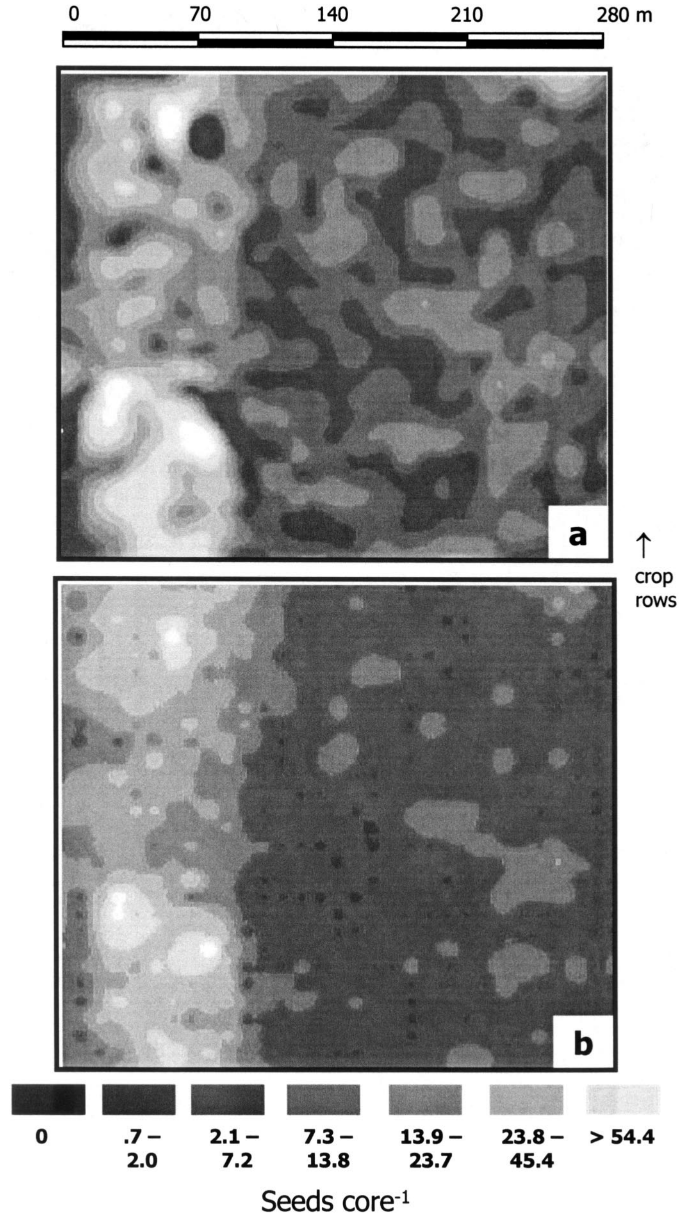

FIGURE 3. Maps generated by kriging (a) and stochastic simulation (b) for a pigweed seed bank in an 8.1-ha block of an irrigated corn field.

Evaluating Sampling Plans

One principle of the IPM paradigm of designing sampling plans that should be retained is cost-benefit analysis to choose the optimal sampling plan. That is, evaluating plans by comparing the cost of sampling to the value of the information obtained for prescribing management (Nyrop et al. 1986). For site-specific weed management, sampling information has value for selecting the best site-specific strategy, with "best" determined by consequences of management such as profit, herbicide use, and crop yield loss from weeds. The weed map is just one type of information needed to predict the consequences of management alternatives; yet, sampling plans and mapping methods are usually compared on the basis of accuracy of a map. This is because evaluating map accuracy requires less time and information and is more straightforward than evaluating the quality of prescribed site-specific management. There are many established procedures for evaluating map accuracy (Isaaks and Srivastava 1989), with commercial software to implement most procedures. However, weed map accuracy may be poorly correlated with the value of the map for prescribing site-specific management. The value of map accuracy for evaluating sampling plans will depend on the resolution and choice of herbicides for site-specific management, the range of weed density in the field, and the critical densities for choosing among management options.

In most cases, prescribing site-specific weed management requires accurate estimates of low yield loss and thereby accurate estimation of a small range of low densities (Oriade et al. 1996). For example, a 10% yield loss in irrigated corn in Colorado may be caused by 2.6 plants m-row^{-1} of common sunflower (*Helianthus annuus* L.), the most competitive weed, or 6.4 plants m-row^{-1} of sandbur [*Cenchrus longis-*

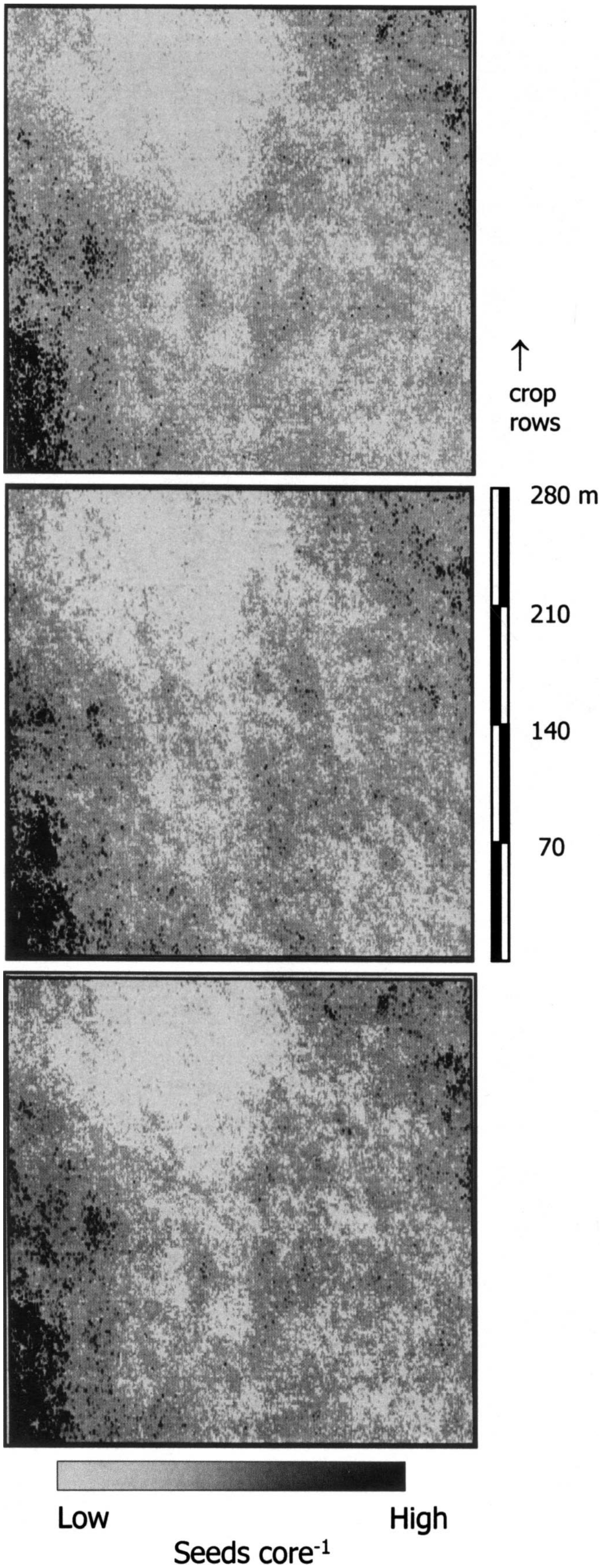

FIGURE 4. Equally probable maps generated by stochastic simulation for a barnyardgrass (*Echinochloa crus-galli* L.) seed bank in an 8.1-ha block of an irrigated corn field.

pinus (Hack.) Fern.], a moderately competitive weed. Errors such as predicting 50 plants m-row^{-1} where actual density is 100 plants m-row^{-1}, or even 10 plants m-row^{-1} where actual density is 15 plants m-row^{-1}, are often irrelevant to the value of the map for prescribing site-specific management because the decision would be to control for all these values. However, conventional methods to evaluate map accuracy do not reflect this perspective. These conventional methods may be more useful for evaluating sampling plans for site-specific weed management if applied to maps of predicted yield loss or maps of categories of density defined for relevance to the management prescription.

Sampling and Mapping as a Process

Mapping weed populations for site-specific weed management will likely only be cost-effective if a grower is committed to site-specific weed management as a way of managing weeds in most fields. Moreover, the grower must be willing to develop weed maps over time using limited sample data supplemented with other data or information that is correlated with the spatial distribution of weed populations in a field. Auxiliary data are only valuable if less expensive than observations of the weed population such as data collected for another use. Potentially valuable auxiliary information may be qualitative or quantitative, including aerial photographs (Lamb and Weedon 1998), sample data from previous years (Colbach et al. 2000b; Dille et al. 2002b; Gerhards et al. 1997; Goudy et al. 2001; Wyse-Pester et al. 2002), georeferenced maps of field characteristics such as soil properties or topography (Dille et al. 2002b; Medlin et al. 2001; Walter et al. 2002), and growers' knowledge of the distribution of weeds in a field (Stafford et al., 1996; Wiles et al. 1998) and past spatially variable management (Wiles and Schweizer 2002; Wyse-Pester et al. 2002). This auxiliary information may be explicitly used in the process of making a map with procedures such as cokriging or indicator kriging (Heisel et al. 1999; Rossi et al. 1993; Walter et al. 1997) or used to target sampling to areas where there is the most uncertainty about optimal management or that are most favorable for an invading species.

Past weed maps and other historical information about the distribution of weeds in a field may be valuable auxiliary information for making a weed map and will become more valuable as we learn more about the spatial dynamics of weed populations. Patches of some weeds are stable in the location, although density in the patch may vary between years (Cardina et al. 1997). However, the weed population in a field varies with time of crop emergence and use of soil-applied herbicides and other management practices (Wiles and Schweizer 2002; Wyse-Pester et al. 2002). Consequently, only selected past maps may be valuable each season for reducing the cost of sampling and targeting sampling to areas where there is the most uncertainty about the optimal management. When updating a past map with new observations seems appropriate, updating will require fewer observations than making a map (Audsley and Beaulah 1996; Hausler and Nordmeyer 1999; Walter et al. 1997) and sampling for updating will likely be less structured and more dependent on observations (adaptive). For example, a sampling plan may prescribe the most intensive sampling to determine whether the known patches have expanded along

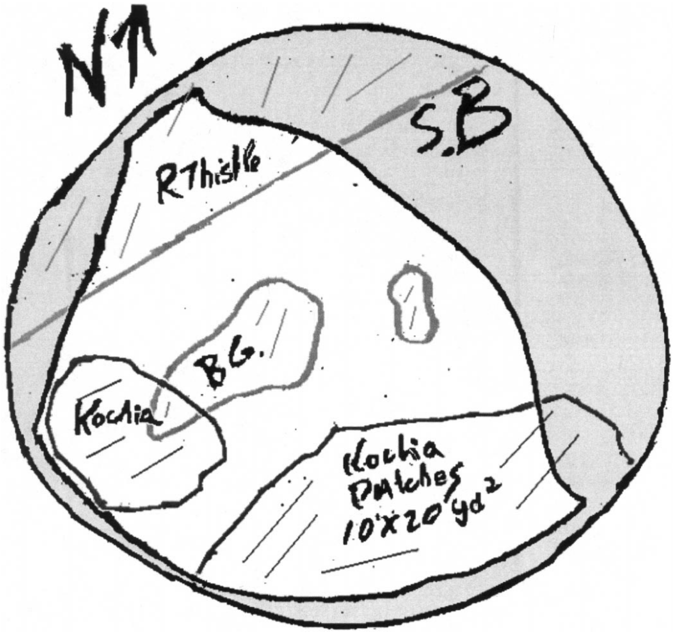

FIGURE 5. Map drawn by an agricultural consultant of the spatial distribution of weeds in an irrigated corn field. Weed patches drawn are barnyardgrass (BG in the map), sandbur (S.B.), kochia [*Kochia scoparia* (L.) Schrad.], and Russian thistle (*Salsola iberica* Sennen & Pau) (R. Thistle).

with less intensive but more structured sampling to determine whether control of each patch is economically justified. Sampling to detect new satellite patches would be the most adaptive, with unplanned observations around each newly discovered patch. Weed counts or quantitative ratings may be needed within the patch, with qualitative assessments sufficient elsewhere.

The knowledge accumulated by growers and agricultural consultants could be more valuable as past weed maps for prescribing site-specific weed management. My experience is that growers and agricultural consultants are aware of variation in the distribution of weeds in their fields, and although only some draw maps, most make management decisions based on their perceptions of the distribution and many will readily draw a weed map if asked (Wiles et al. 1998) (Figure 5). Also, growers and agricultural consultants know about variation in crop rotation within a field, manure applications, mistakes in applying herbicides, and other past practices that might have influenced the spatial distribution of weed populations. For example, soil compaction from an old road influenced the spatial continuity of pigweed (primarily *Amaranthus retroflexus* L.) and grasses and in an irrigated corn field (Wiles and Schweizer 2002) (Figure 6). When spatial continuity varies within a field, each area should be mapped separately to accurately represent the distribution of the weed population (Isaaks and Srivastava 1989). With prior knowledge of the location of the road, sampling could have been more cost-effective. With the square grid used, there was not enough information to describe spatial continuity in the direction perpendicular to the crop row in the area of the old road. Assuming spatial continuity was uniform throughout the field produced questionable maps for some species.

Weed scientists may have not yet used the knowledge of growers and agricultural consultants for making maps because they are unaware of methods to use this information

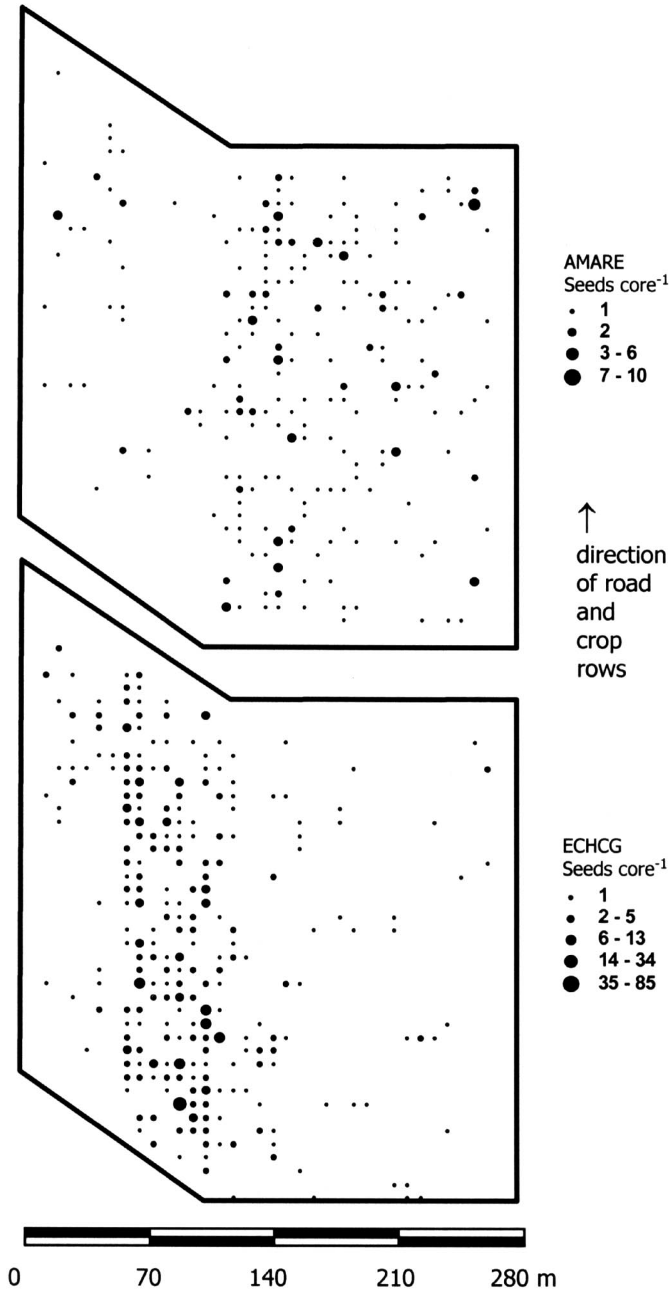

FIGURE 6. Posting of weed seedling data from an 8.1-ha block of an irrigated corn field illustrates that past management can influence spatial continuity. There were more barnyardgrass and less pigweed seedlings in an area in the field that was at one time a road.

with their quantitative, georeferenced data. There are methods to make maps from both qualitative and quantitative information (Isaaks and Srivastava 1989; Rossi et al. 1993); the challenge will be interpreting qualitative information because the perception of terms such as "low," "medium," and "high" density or pressure varies among decision makers (Wiles et al. 1998). Also, some scientists may think the knowledge of growers and agricultural consultants is too imprecise to improve the accuracy of a map made from sample data or even the cost-effectiveness of sampling. However, with prescribing site-specific management as the objective of sampling and the high cost of sample data, this low-cost information may be accurate enough, depending on the objective and implementation of site-specific management.

Sampling Plans and Adoption of Site-specific Weed Management

Adoption of site-specific weed management will be determined by the sampling plans weed scientists develop because a sampling plan is designed for a particular implementation of site-specific weed management. Potentially valuable site-specific weed management may be as simple as applying different herbicides to halves of a field, up to using sophisticated technology for applying varying rates of one or more herbicides. Lack of cost-effective sampling plans prevents adoption of nearly all implementations of site-specific weed management.

For maximum adoption of site-specific weed management, we must develop many different methods for sampling and making maps for the range of available time, resources, and technological sophistication of growers willing to do site-specific weed management. Sampling and mapping with expensive, sophisticated technology may be cost-effective and needed to reduce herbicide use with site-specific management for some cropping systems, but inexpensive, simple technology may be sufficient for other systems. For example, remote sensing may be affordable only as sample data for cropping systems with low profit margins rather than continuous sensor data. The sample data might be a set of intermittent images collected using a simple digital camera synchronized with a hand-held gps unit.

Scientists must then demonstrate the cost-effectiveness of various proposed methods for sampling and mapping to decision makers and us. Currently, most growers say they never have and never will count weeds or have seed bank samples analyzed to make maps for site-specific weed management. However, many growers do collect soil samples and pay for expensive analysis for management of nematodes because they are convinced this is cost-effective. If we do not evaluate and demonstrate the cost-effectiveness of various proposed methods, adoption of site-specific weed management might be limited to growers who enjoy using sophisticated technology. Weed scientists may also spend their limited time and resources on this sophisticated technology and miss opportunities to develop less sophisticated but more cost-effective strategies for site-specific weed management that might be adopted by a wider range of growers.

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